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2013 J. Phys.: Conf. Ser. 476 012035

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Piezoelectric Materials for Nonlinear Energy Harvesting Generators

S Neiss, F Goldschmidtboeing, M Kroener and P Woias

Laboratory for Design of Microsystems, IMTEK, University of Freiburg, Georges-Koehler-Allee 102, 79110 Freiburg, GERMANY

E-mail: sebastian.neiss@imtek.uni-freiburg.de

Abstract. Nonlinear piezoelectric energy harvesting generators can provide a large bandwidth combined with a good resonant power output. In an experimental study, the influence of the piezoceramic material on these two parameters is investigated. The results prove hard piezoceramics to be better suited as converting element compared to soft piezoceramics. Their improved mechanical quality compensates for their low piezo-mechanical coupling leading to both, a larger bandwidth and a higher power output of the generator.

1. Introduction

Nonlinear mass-spring systems have found growing interest in recent research for vibrational energy harvesting [1, 2, 3, 4]. In contrast to linear vibrational generators, a nonlinear stiffness is intentionally introduced in the system. By this, such systems inherently comprise a large bandwidth combined with a good resonant power output [1, 2]. This distinguishes them from linear devices which show a contrary behavior of bandwidth and conversion efficiency [3]. As a consequence, generators with a nonlinear restoring force are better suited for energy harvesting from vibrations with a varying dominant frequency compared to a device with a linear stiffness.

Current research on nonlinear generators is mainly focused on the system dynamics. However, there is no investigation of the influence of the different system components on overall performance. Only Mann [2] points out that strong mechanical damping can suppress beneficial nonlinear effects. This work investigates the influence of soft and hard piezoceramic materials on bandwidth and power output of a nonlinear energy harvesting device using the example of lead zirconium titanate (PZT). The two material categories differ strongly in the mechanical and piezoelectric properties. Soft piezoceramics are characterized by a high mobility of the ferroelectric domains while hard piezoceramics are characterized by lower mobility of the single domains. As results, soft ceramics show stronger piezoelectric coefficients but a lower mechanical quality compared to hard ceramics. In this work, an experimental approach to determine the best material choice based on frequency response and power curve measurements is proposed.

2. Theory

The dynamic displacement $z\,(t)$ of mechanical oscillators with nonlinear stiffness under external excitation F_{ext} is usually described by the Duffing equation:

$$m \cdot \ddot{z}\,(t) + c \cdot \dot{z}\,(t) + k_1 \cdot z\,(t) + k_3 \cdot z\,(t)^3 = F_{\text{ext}} \cdot \cos\,(\omega \cdot t) \tag{1}$$

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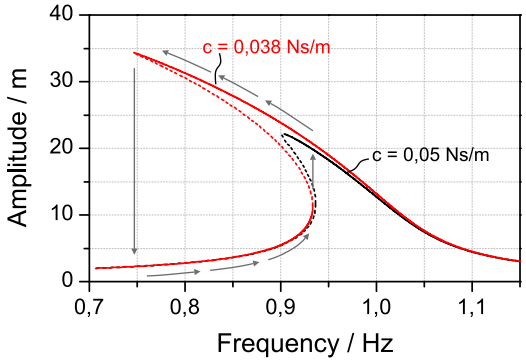

Figure 1. Frequency responses of systems with $k_1 = 1\,\mathrm{N/m}$, $m = 1\,\mathrm{kg}$, $F_{\mathrm{ext}} = 1\,\mathrm{N}$, and $k_3 = -0.0005\,\mathrm{N/m^3}$ for two different damping constants.

In this equation, m is the effective mass, c is the damping constant, and k_1 and k_3 are the linear and nonlinear spring constants, respectively. Such systems are classified depending on the type of the non-linearity as softening ($k_3 < 0$) or hardening ($k_3 > 0$).

Figure 1 shows two frequency responses of systems with softening characteristic and different damping constants. The characteristic hysteresis loop is indicated with arrows. The graph shows the strong difference in bandwidth between the two systems. A small overall damping leads to a strongly increased bandwidth and displacement amplitude.

Consequently, the overall damping of the nonlinear device has to be minimized in order to obtain a large bandwidth. For an energy harvesting device, the overall damping is the sum of the oscillator's mechanical damping and the electrical damping caused by the load. However, electrical damping depends on the piezoelectro-mechanical coupling present within the system. A strong coupling can increase the output power but will also increase the electrical damping and thus reduce the bandwidth. As a consequence, the choice of the piezoceramic material has a strong influence on the dynamic behavior of the system.

3. Nonlinear generator

The characterized harvester comprises two parts. The generator itself is shown schematically in figure 2. It is made of a laser-cut steel spring (1.4310 steel) with the ceramic glued at the base of the spring. Generators with hard PZT ceramic (PIC181, PI GmbH) and soft PZT ceramic (PIC255, PI GmbH) are fabricated. A soft-magnetic proof mass with a triangular shape made of pure iron is additionally attached to the free end of the beam.

The nonlinear stiffness is generated by the magnetic spring which is shown schematically in figure 3. The proof mass oscillates in the gap of the magnetic circuit. The total reluctance of the circuit is a function of the position d of the mass which leads to a restoring force F on

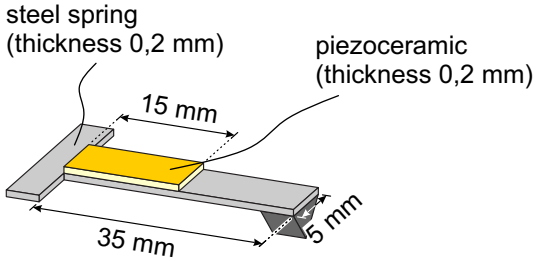

Figure 2. Schematic of the fabricated generator.

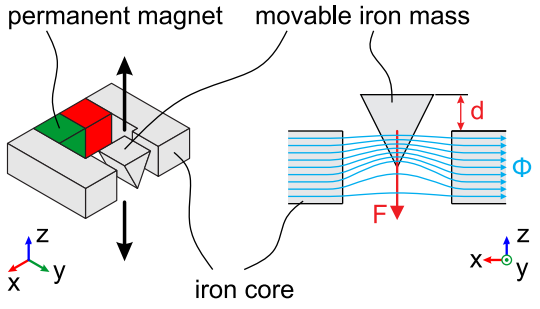

Figure 3. Schematic of the nonlinear magnetic spring.

it [5]. Depending on its geometry and idle position, a nonlinear restoring force on the proof mass is obtained [6]. All parts of the circuit are made of pure iron and have a cross section of $(5 \times 5)\,\mathrm{mm}^2$. The gap between proof mass and iron core is 0.3 mm and the magnet is a NdFeB permanent magnet (N35, $B_r = 1.17\,\mathrm{T}$).

Figure 4 shows the configuration of the two components in the measurement setup. The idle state of the mass is located about 0.5 mm beneath the top edge of the magnetic spring.

4. Dynamic characterization

Two different measurements are conducted to determine bandwidth and power output of the generators. A frequency response measurement in open-loop configuration is used to determine the influence of the ceramic's mechanical quality on the bandwidth. In addition, a power curve is recorded to measure the maximal output power. In this measurement both, piezoelectrical and mechanical properties affect the measurement results.

The test setup is shown schematically in figure 5. The generator is mounted to a shaker (TV51110, TIRA GmbH) as shown in figure 4. The sinusoidal input signal is measured with an acceleration sensor (Typ8636C5, Kistler AG). The piezoelectric voltage is measured with a PC interface (NI DAQmx9172). In addition, a resistance decade box can be used to record power curves.

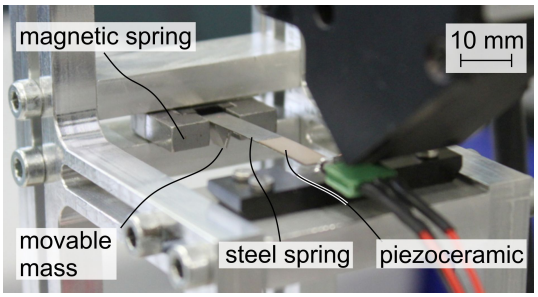

Figure 4. Picture of the generator with magnetic spring.

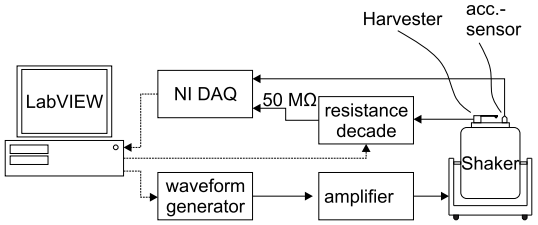

Figure 5. Schematic of the measurement setup.

5. Frequency response

Figure 6 shows the frequency response of the open-loop voltage for generators with both types of piezoceramics at a sinusoidal excitation with a peak acceleration of $5\,\mathrm{m/s^2}$. The generator with hard piezoceramic has a slightly higher resonance frequency which is caused by the higher stiffness of the ceramic. Also, the hard ceramic transducer delivers a larger bandwidth compared to the soft ceramic transducer. As a measure for the bandwidth of the system, we introduce the relative hysteresis width:

$$H = \frac{f_{\mathrm{jump,up}} - f_{\mathrm{jump,down}}}{f_{\mathrm{jump,up}}} \tag{2}$$

The generator using a hard piezoceramic transducer reaches a values of $H = 10.9\,\%$ while the generator using a soft ceramic reaches a values of only $H = 4.7\,\%$. Since there is no electrical damping involved, the increased bandwidth is a result of the better mechanical quality of the hard ceramic. In addition, the hard ceramic also produces a larger output voltage. However, since the displacement amplitude is larger as well, this is not a result of a better piezoelectro-mechanical coupling.

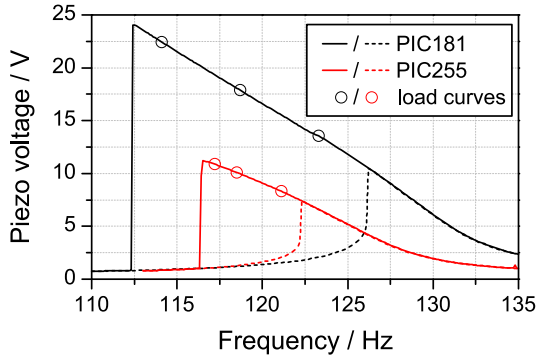

Figure 6. Measured frequency response for vibrational generator with hard piezoceramic (PIC181) and soft piezoceramic (PIC255) under sinusoidal excitation with a peak acceleration of 5 $^{m}/_{s^2}$. Solid lines indicate a frequency down-sweep and dashed lines an frequency up-sweep, respectively.

6. Power curves

Power curve measurements at a peak acceleration of 5 $^{m}/_{s^2}$ are shown in figure 7 for the generator with hard ceramic and in figure 8 for the generator with soft ceramic, respectively. The power curves are obtained for both, an up-sweep of the load resistance and a down-sweep of the load resistance. Prior to the measurement, the working point of the generator is set in a frequency down-sweep to be located on the upper branch of the frequency response.

For both harvester types, the power output shows an abrupt break-in at a certain load for an operation frequency close to the open-loop jump-down frequency. This is a result of the increasing electrical damping which leads to a reduction of the bandwidth. At the critical load, the system's bandwidth is reduced beneath the point of the operation frequency and the oscillation drops to the low power state. Only when increasing the operating frequency to a certain level, the optimal load resistance can be used to extract electrical energy from the system.

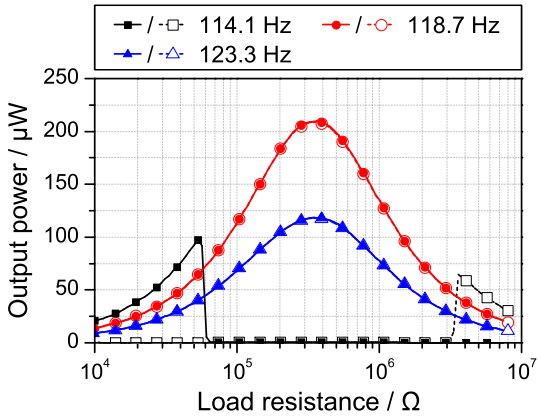

Figure 7. Power curves for a vibrational generator with hard piezoceramic (PIC181). Solid lines indicate a frequency down-sweep and dashed lines a frequency up-sweep, respectively.

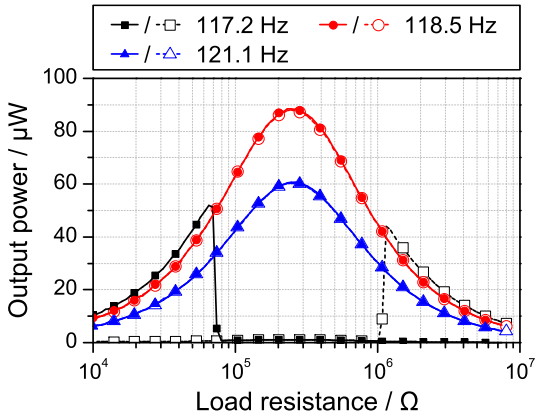

Figure 8. Power curves for a vibrational generator with soft piezoceramic (PIC255). Solid lines indicate a frequency down-sweep and dashed lines a frequency up-sweep, respectively.

The power curve measurements show that the optimal load resistance differs for an up-sweep and a down-sweep of the load at excitation frequencies close to the jump-down frequency. Thus, the generator cannot be operated in the frequency range close to the open-loop jump-down region. To obtain the maximum working range, power curves are recorded for several frequencies in the bistable region. The optimal up- and down-sweep load resistance obtained

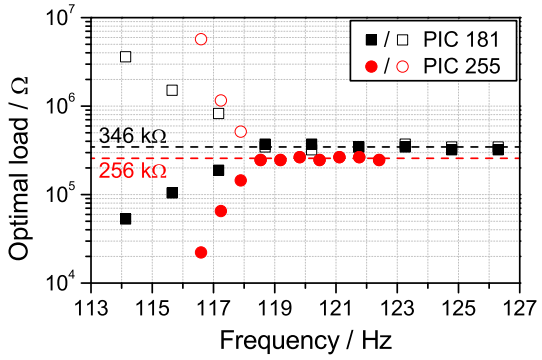

Figure 9. Optimal load resistance at different excitation frequencies for vibrational generator with hard piezoceramic (PIC181) and soft piezoceramic (PIC255) at a peak acceleration of 5 m/s^2. Filled markers correspond to an up-sweep of the resistance and hollow markers to a down-sweep of the resistance, respectively.

in these measurements is plotted against the excitation frequency in figure 9. The maximum working range is given as the region without bifurcation in optimal load resistance. In addition, the maximum power output and optimal load resistance can be determined. The system with the hard piezoceramic transducer still reaches a relative hysteresis width of $H = 5.9\,\%$ at an optimal load resistance of 346 kΩ and a maximum output power of 210 µW. The generator with soft piezoceramic transducer only reaches a relative hysteresis width of $H = 3.1\,\%$ at an optimal load resistance of 256 kΩ and a maximum output power of 88 µW.

7. Conclusion

The results of the frequency response measurements show the superior mechanical quality of hard PZT ceramics. They lead to an approximately twofold open-loop bandwidth and voltage amplitude compared to soft PZT ceramics. Thus, the energy in the system with hard ceramic is approximately four times as much as in the soft ceramic generator. However, power curve measurements show that hard ceramics only extract about 2.4 times more electrical energy from the oscillation compared to soft ceramics which means that electro-mechanical coupling is stronger in generators with soft ceramics. Still, the lack of electro-mechanical coupling in hard ceramic generators is over-compensated by the lower mechanical damping giving to an increased power output.

Acknowledgments

We gratefully acknowledge the financial support from the German Research Association (DFG) within the Research Training Group (GRK) 1322 "Micro Energy Harvesting".

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